Applying a social-ecological system framework to diagnose drivers of dingo management practices

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ABSTRACT

Social-ecological system (SES) frameworks offer a way of diagnosing the economic, environmental, and social issues driving human-canid conflict, and can assist in the development and testing of management interventions. SES-based approaches to carnivore management in the context of conflicts with humans are limited and highlight a growing need to develop new initiatives involving a broad spectrum of interested parties. To help identify management opportunities provided by using a SES applied to human-canid conflict, we apply the principles of Elinor Ostrom's multi-tiered framework and develop a SES relating to dingo management in the Australian rangelands. This SES posits variables influencing management practices for dingoes and identifies key management opportunities. We use the framework to categorise first-tier sub-components of the SES, propose second-tier variables specific to the SES (referring to past history or experiences of relevant actors and government resource policies), and identify pathways or interactions for testing (e.g., the influence of scientific evidence on policy, development of educational packages, uptake of new knowledge, and impact of socio-economic status). The proposed SES demonstrates the potential for such approaches to help resolve human-dingo conflict, highlights variables that may influence dingo management practices, and presents opportunities for testing these variables empirically.

Key words: Dingoes; carnivores; human-wildlife conflict; practice change; predator management; systems-based approaches.

DOI: https://doi.org/10.7882/AZ.2020.036

Introduction

The influence of apex predators on ecosystems is globally topical (e.g., Ripple *et al.* 2014; Leo *et al.* 2019), with human-carnivore conflicts well documented (e.g., Treves *et al.* 2004; Ekernas *et al.* 2017). In examining these conflicts, it is important to understand social and ecological factors important to carnivore management (Lischka *et al.* 2018), especially as calls for increased tolerance of carnivores are rising (e.g., Reiter *et al.* 1999; Manfredo *et al.* 2009; Treves and Bruskotter 2014; van Eeden *et al.* 2018a). However, promoting tolerance while addressing socio-economic factors (Vitali 2014) requires management frameworks that are mutually beneficial for carnivores and humans. These approaches should be adaptive to changing conditions (e.g., climate; new knowledge; new technologies; societal attitudes) and align with principles for stakeholder engagement (e.g., Braysher 2017). This paper reviews social-ecological system (SES) approaches to carnivore management and applies an established framework to a proposed dingo-pastoralist SES in the South Australian rangelands. It aims to show how systems-based approaches can categorise and help resolve human-carnivore conflict. This approach enables us to examine various possible management strategies, including facilitating coexistence between people and dingoes in line with principles of current 'rewilding' initiatives involving wolves (*Canis lupus*) in Europe and North America (Wolf and Ripple 2018). Currently, much of the management of dingo-livestock conflict in Australia focuses almost exclusively on lethal predator control (van Eeden *et al.* 2018a, b; Philip 2020).

Boronyak *et al.* (2020) identified several rationales for building coexistence capacities in extensive rangeland livestock production systems. They present the economic

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argument that livestock production is a dominant terrestrial land use, but ecological considerations include the counter contention that large carnivores provide critical contributions to ecological functions in these areas. Boronyak *et al.* (2020) argue that persecution of large carnivores over many decades has produced considerable ethical, welfare, reputational and social costs, and that an increasing body of evidence shows that lethal control may be counter-productive to reducing predation risk to livestock. Consequently, the adoption of non-lethal measures and the creation of an enabling environment to address entrenched positions in the debate about the management of large carnivores are being proposed (Smith and Appleby 2018; Smith *et al.* 2020).

We suggest that these arguments are best addressed via systems-based approaches. SES can contribute to objective decision making by providing inputs that address the varied perspectives of stakeholders. For example, the attitudes and perceptions of graziers affected directly by loss of livestock to dingo predation may differ markedly from those of conservationists and urban residents whose livelihoods are not affected (König *et al.* 2020). We examine the potential of an established SES framework to address dingo-human conflict in the arid rangelands of Australia and propose a conceptual dingo-pastoralist SES to illustrate its applicability.

Social-ecological system (SES) approaches to carnivore management

Binder *et al.* (2013) recognised ten frameworks for analysing SES. These frameworks are essentially tools for identifying the social, economic, and environmental factors influencing environmental issues, and all enable structured, interdisciplinary reasoning regarding complex problems in SES. They vary with respect to contextual and structural criteria, such as how they conceptualise the systems and their interrelations.

Pioneering work on these frameworks was completed by Elinor Ostrom and associates in the 1980s and 1990s (e.g., Ostrom 1994). Subsequently, this research was refined and expanded to include work on ideas from theories relating to the study of resilience, robustness, sustainability, and vulnerability (Berkes *et al.* 2008; Ostrom 2009; Binder *et al.* 2013; Thiel *et al.* 2015; Partelow 2018). In drawing upon this body of work we contend that such frameworks can assist in the development and testing of management interventions for resolving dingo-pastoralist conflict as they provide a systematic means of categorising the inherent complexities of human-dominated systems to "diagnose" environmental problems (Liu *et al.* 2007; Guerrero and Wilson 2017). Identifying these complexities is important because practice change is not achieved solely through traditional science nor by education-based interventions alone (Pooley *et al.* 2016) as these processes do not necessarily address drivers of human behaviour, and often fail to acknowledge multiple legitimate perspectives (Gilmour *et al.* 2015; Addison and Pavey 2017).

Of the ten frameworks discussed by Binder *et al.* (2013), the SES framework developed by Ostrom is referred to as "providing a common language for case comparison for organizing the many variables relevant in the analysis of SES into a multitier hierarchy that can be unfolded when needed, and for facilitating the selection of variables in a case study" (p. 25). Hence, it is this framework that has been pivotal to explaining sustainable outcomes in the management of land-based resources. Key characteristics include conceptualisation of the social system (both at a micro- and macro-level), and the interaction and feedback loops between social and ecological systems. It includes the social and governance structures that affect how actors behave, including their role in the governance system and how they can help to shape it. The framework combines ecological and social elements and the reciprocity between them. It contains a dynamic component (pp. 24-26) and is "the only framework that, despite its origin in the social sciences, provides the option to treat the social and ecological systems in almost equal depth" (p. 25). In addition, "… it provides a frame for developing different degrees of specificity in differentiating different tiers" (p. 26).

SES approaches based directly on Ostrom's formulation have been used extensively to categorise forestry and fisheries resource systems, originally evolving as a means of framing systems in the context of common pool resources (Ostrom 2007; Basurto and Ostrom 2009; Ostrom 2009; Basurto and Nenadovic 2012). Such approaches have also been employed when examining challenges associated with human-wildlife interactions (e.g., management of moose (*Alces alces*) in Canada (Dressel *et al.* 2014)). However, relatively few published examples of the explicit use of SES to categorise human-carnivore conflict exist (see Appendix 1). This paucity was highlighted by a recent meta-analysis of global research on human-carnivore conflict mitigation, where approaches focused almost exclusively on bio-physical or economic methods to offset stock losses (van Eeden *et al.* 2018a). Most of these studies focused on conflicts involving felids; others identified conflicts involving ursids, canines, and mustelids. Conflicts included illegal poaching of carnivores, garbage-raiding by carnivores, and overall declines in carnivore populations (Winterbach *et al.* 2012). Only one study (Johnson *et al.* 2018) applied a SES approach to resolve conflict in a real-world scenario, although the framework was defined after-the-fact (Lischka *et al.* 2018). No study employed common terminology or concepts (i.e., in line with those defined and recommended by Ostrom 2009 or McGinnis and Ostrom 2014) to categorise their SES.

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Closely related research includes that by Carter *et al.* (2014) who developed a coupled human and natural (CHAN) systems approach to wildlife research and conservation, which is broadly similar to Ostrom's SES framework. They defined a conceptual framework focused on integrating factors influencing human motivations in relation to large carnivore poaching (Carter *et al.* 2017). Similarly, Gálvez *et al.* (2018) proposed a socioecological modelling framework, based on remote sensing, wildlife survey, and social research, to evaluate drivers of the decline of güiña (*Leopardus guigna*) in southern Chile. This approach is similar to that of Wilkinson *et al.* (2020) who proposed an 'ecological framework' to describe ecological drivers of predation on livestock, which includes the biophysical landscape, livestock ecology and carnivore ecology. They highlighted ecological mechanisms (e.g., density-mediated effects, behaviourally mediated effects, and optimal foraging theory) through which specific management interventions operate, analysing ecological determinants of failure and success of management interventions focusing on snow leopards (*Panthera uncia*), wolves, and cougars (*Puma concolor*).

We are unaware of any scenario where a SES framework has moved beyond diagnosis to implement and test interventions to resolve human-canid conflict. However, recent efforts to understand the nature of conflicts involving people and black bears (*Ursus americanus*) in urban North America have employed an approach allied to SES. In that scenario, garbage-related conflict was 60% lower in areas with treatment (distribution of bear-resistant bins; education; increased enforcement) than in control areas (Johnson *et al.* 2018). This research resulted in a conceptual three-tiered SES model of human-wildlife interactions focused on overarching factors (defined as "activities") affecting human-wildlife interactions, external influences on individuals' behaviour, and individual attributes (both of wild animals and humans) that affect behaviour (Lischka *et al.* 2018). While not explicitly a SES approach, in the Amboseli ecosystem of southern Kenya, the Lion Guardians program used an incentive program embedded in a framework that incorporated local community values and belief systems to reduce killings of lions (*Panthera leo*). Hazzah *et al.* (2014) estimated that the program reduced killings of lions by 99% compared with an 87-91% drop estimated for a concurrently running traditional incentives program.

These examples demonstrate the potential for systems-based approaches to achieve changes in practice and offer possibilities for greater testing and implementation of non-lethal (and potentially more effective) approaches to carnivore management. Yet, doing so remains challenging given the complexities of human-wildlife conflict, including the diversity of contexts and species, and people's attitudes toward wildlife, perceptions of risk, personal experience, and social factors, such as religious affiliation, ethnicity, and culture (Dickman 2010; van Eeden *et al.* 2018b). However, conceptual frameworks outlining the SES factors influencing human-wildlife conflict, which use psychological and social theory to identify drivers of behavioural change, may influence support for non-lethal approaches (e.g., Baruch-Mordo *et al.* 2009; Bruskotter and Wilson 2013; Martin and Hine 2017).

Developing a dingo-pastoralist SES

History of dingo management

The dingo (variously described as *Canis dingo, C. familiaris,* and *C. lupus dingo*, among others; see Kreplins *et al.* 2019) is Australia's largest terrestrial carnivore, and was likely introduced to Australia around 5000 years ago (Smith and Savolainen 2015). The species has been controlled across most of the continent since European settlement because the dingo preys upon livestock, and particularly sheep (Allen and Sparkes 2001; Prowse *et al.* 2015). Despite concentrated efforts to control dingoes lethally, they remain relatively abundant over much of mainland Australia (Stephens *et al.* 2015). Maintaining dingo populations, at least in some circumstances, is important because the dingo is a naturalised animal of cultural and historical significance (Smith 2015), and as an apex predator, may influence the structure and function of ecosystems (Newsome *et al.* 2015). Large canids, including dingoes, influence ecosystem processes by restricting the abundance of wild herbivores, such as macropods. In particular, predation by dingoes likely ameliorates grazing pressure on vegetation (Letnic *et al.* 2012), potentially benefitting sheep and cattle by reducing competition for food and water (Prowse *et al.* 2015), and may also benefit livestock industries by reducing negative impacts from meso-predators, such as red foxes, *Vulpes vulpes* (e.g., Leo *et al.* 2015).

Increasingly, attempts are being made to find pathways toward human–wildlife coexistence (Marchini *et al.* 2019) and co-adaptation (Carter and Linnell 2016). Co-existence implies the existence of "a dynamic, but sustainable state in which humans and wildlife co-adapt to living in shared landscapes, where human interactions with wildlife are governed by effective institutions that ensure long-term wildlife population persistence, social legitimacy, and tolerable levels of risk" (König *et al.* 2020, in press). Yet, conflict between the livestock sector and dingoes remains a pervasive narrative that has proved extremely difficult to break down.

Dingo management practices

Analysis of historical records by van Eeden *et al.* (2019b), Philip (2019), and Philip (2020) revealed a long history of lethal control of dingoes, but particularly since the 1950s. The four most popular management methods employed to protect livestock from dingoes were trapping, ground-baiting, fencing, and shooting. The most common strategy included aerial poison baiting programs and fencing.

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Rearing sheep was the strongest determinant of what management methods were used, with sheep graziers less likely to use ground-baiting and shooting and more likely to use trapping and fencing. This practice may reflect the fact that sheep graziers were concerned with protecting working sheep dogs from accidental poisoning. van Eeden *et al.* (2019b) argued that some historical attitudes and practices towards dingoes have endured, with dingo attacks on livestock continuing to be regarded as a major threat by graziers. Given that poisoning of dingoes was first recorded in 1814, some practices have persisted for over two centuries (Phillip 2019), which is evident in a survey by van Eeden *et al.* (2019a) in which ground-baiting and shooting continued to form a major focus of management by Australian graziers. Only three of 23 respondents concentrated solely on non-lethal methods (e.g., animal husbandry or livestock guardian animals) and indicated that they supported maintaining dingoes in the landscape.

Lethal control methods are frequently justified on utilitarian grounds (Ramp and Bekoff 2015) despite growing ethical concerns voiced by environmental and animal welfare groups (Philip 2019) and questions around the efficacy of these methods (Stone *et al.* 2017; van Eeden *et al.* 2018a, 2018b). The Australian livestock industry itself is increasingly developing a sustainability discourse to assist in selling its products, which is not necessarily enhanced by the ongoing use of lethal control measures. However, proposing and testing non-lethal methods for carnivores such as dingoes is challenging, not only because of the direct (livestock and income loss) and indirect (stress and trauma associated with livestock killings) effects (Ecker *et al.* 2016), but also because of the strongly held values and beliefs of people living and working in associated SES. Doing so is further complicated by the ongoing debate about the role of dingoes, wild dogs, and their hybrids (see Allen *et al.* 2011; Letnic *et al.* 2011; Glen 2012; Allen *et al.* 2013a; Johnson and Ritchie 2013; Allen *et al.* 2015; Smith 2015; Allen *et al.* 2017) in suppressing smaller exotic meso-predators, such as cats (*Felis catus*) and red foxes, the efficacy of methods used to evaluate that role (e.g., Allen *et al.* 2013b; Fleming *et al.* 2013; Hayward and Marlow 2014; Johnson *et al.* 2014; Nimmo *et al.* 2015), and dingo classification (Crowther *et al.* 2014; Allen *et al.* 2017; Jackson *et al.* 2017; Ritchie *et al.* 2018; Jackson *et al.* 2019; Smith *et al.* 2019). Some researchers argue that the dingo is not necessarily ecologically positive or beneficial (Allen *et al.* 2013b; Allen *et al.* 2014), and priorities for its management are influenced by social and economic factors as well as ecological ones (Fleming *et al.* 2012).

Current legislation and policy vary among states, territories, and jurisdictions, but dingoes are a declared pest in most, with landholders obliged to kill them except where they occur on certain land tenures (Letnic *et al.* 2012; Smith 2015). The dingo debate largely focuses on the biological and economic implications of dingo management (although see Fleming *et al.* 2012; Wicks *et al.* 2014), but in human-carnivore conflicts social and psychological factors can be more important than biological or economic factors in shaping behaviour, thwarting simple solutions and uptake of interventions (Bisi 2007) or education. SES frameworks can be used to identify these factors and how they interact with the economic and environmental variables influencing dingo management.

A SES framework for resolving dingo-pastoralist conflict

As described earlier, Ostrom's (2007, 2009) SES framework is a multi-tiered classification system developed to identify variables influencing the governance of common-pool resources, and act as a diagnostic tool for elucidating the factors affecting sustainability in complex SES. Effectively (and importantly), it provides a common set of terms for categorising SES and a means of organising knowledge and hypotheses about how a SES functions and why (McGinnis and Ostrom 2014). The framework also offers a tool for predicting the likely outcomes of interacting variables at a given time and place. It includes a set of common "first-tier" sub-components used to define the SES of interest (Figure 1). The framework incorporates additional "second-tier" variables that relate to broader sub-components (Table 1).

To develop the proposed SES focusing on human-dingo conflict, we first identified the relevant tier-one sub-components (as per Figure 1). In our example, the resource system (RS) is the sheep and cattle grazing (pastoral) industry, and the resource unit (RU) of interest is the dingo population. The social, economic, and political setting (S) is pastoral properties in the arid rangelands on either side of the South Australian section of the 5,500-km-long dingo barrier fence (the "dog fence"), installed in the 1880s to exclude dingoes from sheep-grazing areas to its south (Letnic and Koch 2010). The key actors (A) are pastoralists. The governance system (GS) constitutes a leasehold system where pastoralists lease Crown land to raise livestock. The land must be managed sustainably and improved in line with guidelines set out by a pastoral board (Natural Resources South Australian Arid Lands 2017). Dingo management is influenced strongly by the presence of the dog fence. South of the fence, dingoes are a declared pest and must be controlled by pastoralists. On the northern side, control activities are at the discretion of the landholder, although landholders adjoining the fence are required to control dingoes within a 35-km buffer zone (South Australian Wild Dog Advisory Group 2016).

Considering that pastoralists in the region are the actors (A) responsible for daily management of vast areas (Morton *et al.* 1995), and the overarching role of dingo management policy and legislation (S), we wanted to understand what second-tier variables (as per Table 1) might affect adoption of dingo-friendly management

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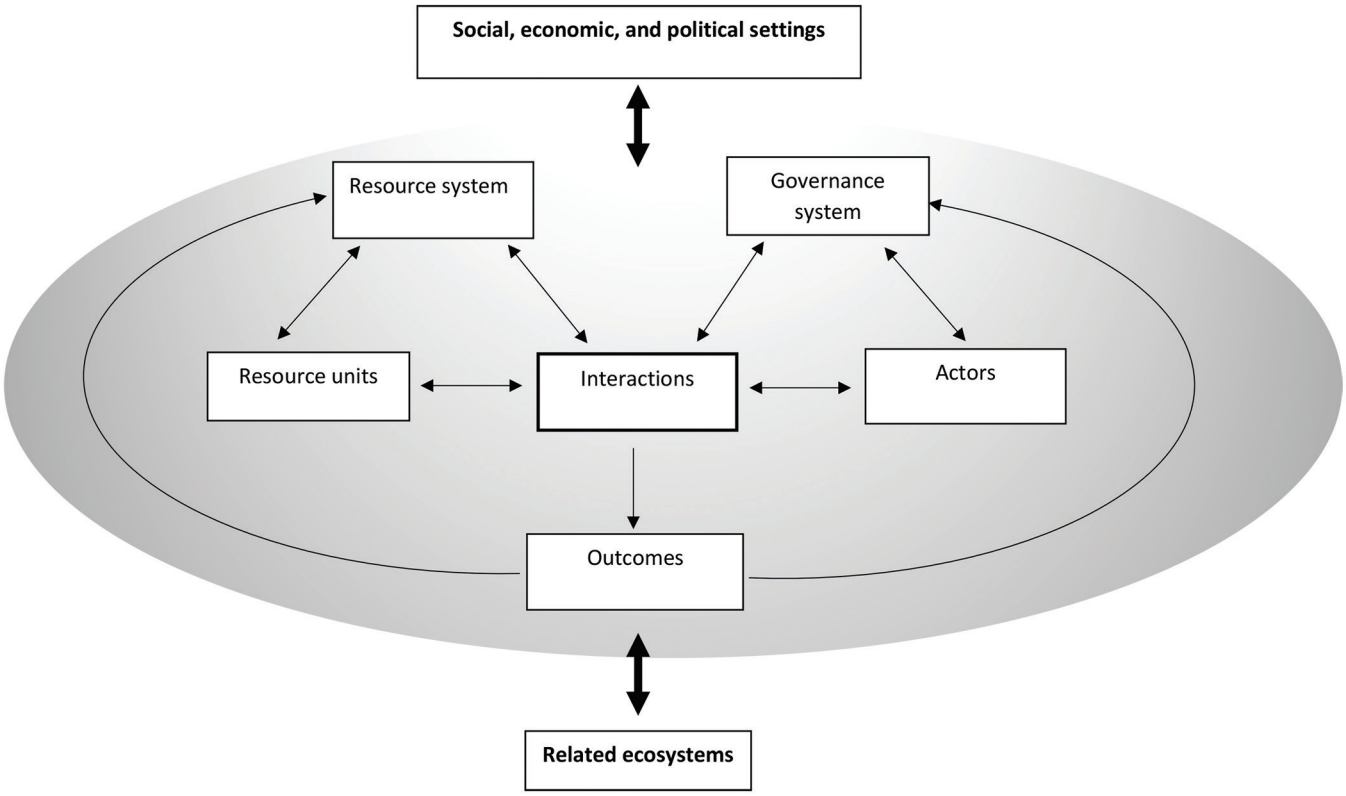

Figure 1. Overarching (tier 1) subsystems used in the SES framework (adapted from Ostrom 2009; McGinnis and Ostrom 2014). Subsystems include: (i) resource system (e.g., fishery; waterbody; rangeland); (ii) the resource units generated by that system (e.g., fish; water; pasture); (iii) the actors key to that system;(iv) the governance system.

practices. In practice, not all second-tier variables are intended to be examined at once. For example, Ostrom (2009) focused on ten variables considered important to understanding common-pool resource problems according to published empirical research. To guide our selection of variables, we posited drivers of dingo management practices for the system of interest. These drivers were based on extrapolation, personal experiences with pastoralist groups, and published empirical research, and are not exhaustive or necessarily "right" or "wrong". We then categorised these variables according to Ostrom's (2007, 2009) definitions (Table 1) and developed a causal-loop (or SES) diagram showing how they may influence dingo management (Figure 1).

The proposed SES (developed to align with the framework developed by Ostrom 2009; McGinnis and Ostrom 2014) demonstrates how interacting variables may affect dingo management (Figure 2). As shown in Figure 2, the factors we identified comprise a range of tier-two variables (Table 1). Common tier-two variables falling under A and S were: A3 (history or past experiences of actors) and S4 (government resource policies). In Binder *et al.*'s (2013) analysis of frameworks for analysing SES, they were characterised in terms of three criteria: (1) whether the framework conceptualises the relationship between the social and ecological systems as uni- or bi-directional; (2) whether the framework takes an anthropocentric or an ecocentric perspective on the ecological system; and (3) whether the framework is action-oriented or analysis-oriented. Following this approach, we characterise the dingo-pastoralist SES as uni-directional. It does not define explicitly the feedback loops and learning processes within the social system that would be triggered by changes in the ecological system. It is (intentionally) analysis-oriented, being developed with the goal of providing a general approach for answering different research questions relating to dingo-pastoralist conflict. It also takes an anthropocentric perspective, with the ecological system largely being defined by its utility for people.

Key features of the proposed dingo-pastoralist SES

We identified legislation/policy, availability of evidence-based education programs, and incentive or stewardship schemes as important S4 variables. Lethal control of dingoes by landholders is a legislated requirement south of the dog fence (South Australian Wild Dog Advisory Group 2016), with a baiting intensity of up to 40 baits per km^2 now recommended for maximum impact (Ballard *et al.* 2020). In practice, control activities in the focal SES can range from low intensity shooting to coordinated baiting programs or may not occur at all (based on landholder requests for poison baits; Allen 2010). Pastoralists often demonstrate a distrust of information presented to them by "external" organisations (Holmes and Day 1995; Addison and Pavey 2017). Models of participation or engagement that focus on filling an "information deficit" rather than negotiating agreed

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outcomes are likely to fail (Blake 1999; Waudby *et al.* 2012; Addison and Pavey 2017). We suggest that an evidence-based approach on its own (drawing on research both in conservation science and social science research on landholders and communities) would be insufficient, but could be efficacious if combined with a participatory approach (de Vente *et al.* 2016). This sentiment (i.e., a desire to be consulted as stakeholders with legitimate knowledge and experience of the issue at hand) has been expressed by pastoralists in other studies (e. g., Waudby *et al.* 2012). Currently, no incentive exists for converting to non-lethal dingo management practices. Such a program is unlikely until a change in legislation occurs, although some parties have sought to establish dingo-friendly management regimes on cattle properties in the area (Wallach *et al.* 2017). Financial

Table 1. Second tier variables of the SES framework (drawn from Ostrom 2009; McGinnis and Ostrom 2014).

Social, economic and political settings (S)
S1– Economic development
S2 – Demographic trends
S3 – Political stability
S4 – Government resource policies
S5 – Markets
S6 – Media organisations
S7 – Technology

Governance system (GS)
GS1 – Government organizations
GS2 – Non-government organizations
GS3 – Network structure
GS4 – Property-rights systems
GS5 – Operational rules
GS6 – Collective choice rules
GS7 – Constitutional rules
GS8 – Monitoring & sanctioning processes

Resource system (RS)
RS1 – Sector (e.g., water, forests, pasture, fishery)
RS2 – Clarity of system boundaries
RS3 – Size of resource system
RS4 – Human-constructed facilities
RS5 – Productivity of system
RS6 – Equilibrium properties
RS7 – Predictability of system dynamics
RS8 – Storage characteristics
RS9 – Location

Resource units (RU)
RU1 – Resource unit mobility
RU2 – Growth or replacement rate
RU3 – Interaction among resource units
RU4 – Economic value
RU5 – Number of units
RU6 – Distinctive characteristics
RU7 – Spatial & temporal distribution

Actors (A)
A1– Number of actors
A2 – Socioeconomic attributes of actors
A3 – History or past experiences of actors
A4 – Location
A5 – Leadership/entrepreneurship
A6 – Norms (trust-reciprocity)/social capital
A7 – Knowledge of SES/mental models
A8 – Dependence of actors on resource
A9 – Technologies available to actors

Interactions (I)
I1 – Harvesting
I2 – Information sharing among actors
I3 – Deliberation processes
I4 – Conflicts among actors
I5– Investment activities
I6 – Lobbying activities
I7 – Self-organising activities
I8 – Networking activities
I9 – Monitoring activities
I10 – Evaluative activities

Outcomes (O)
O1 – Social performance measures (e.g., efficiency, equity, accountability, sustainability)
O2 – Ecological performance measures (e.g., overharvested, resilience, biodiversity, sustainability)
O3 – Externalities to other SES

Related ecosystems (ECO)
ECO1 – Climate patterns
ECO2 – Pollution patterns
ECO3 – Flows into and out of focal SES

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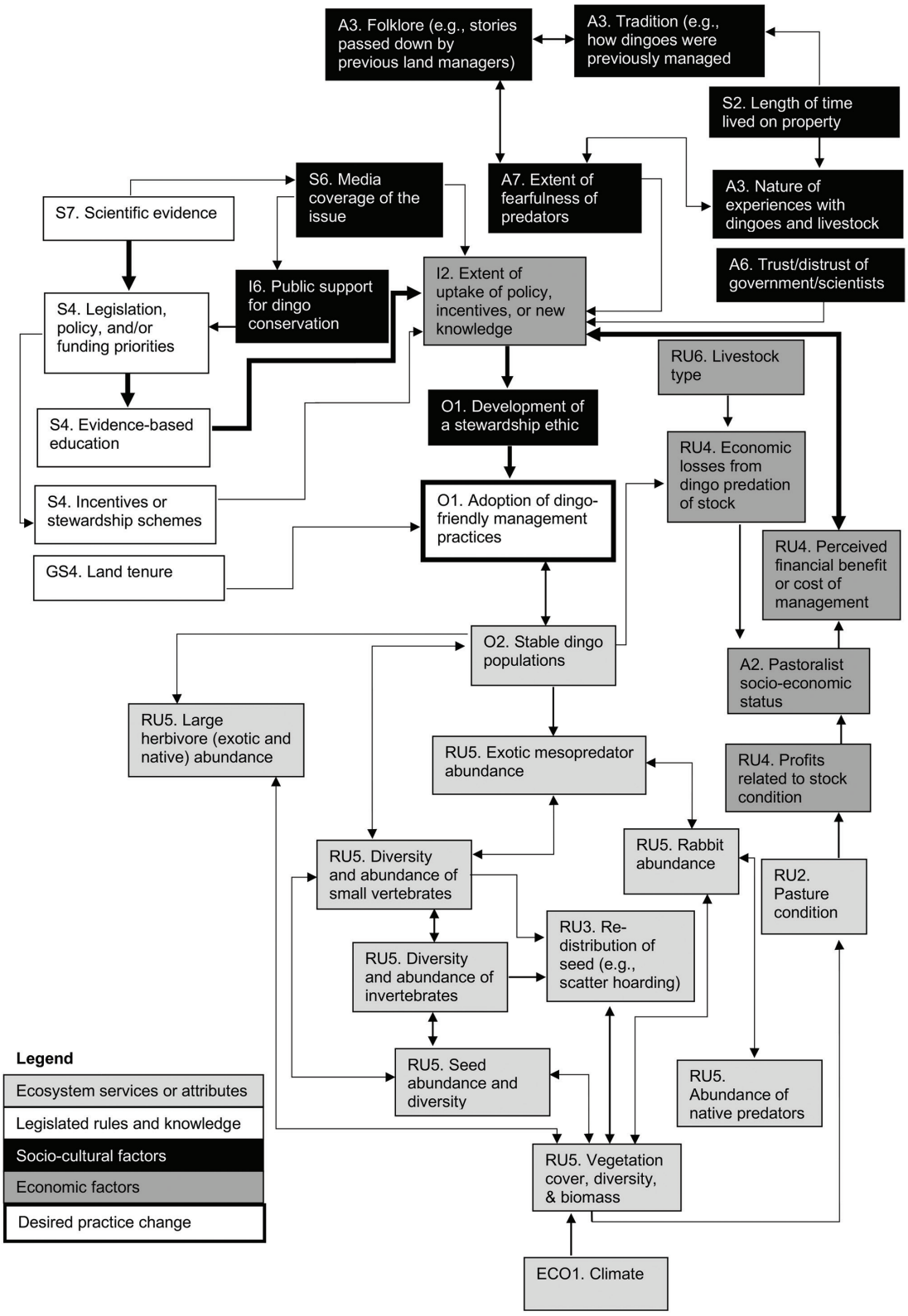
A3. Folklore (e.g., stories passed down by previous land managers)
A3. Tradition (e.g., how dingoes were previously managed
S2. Length of time lived on property
S6. Media coverage of the issue
A7. Extent of fearfulness of predators
A3. Nature of experiences with dingoes and livestock
S7. Scientific evidence
A6. Trust/distrust of government/scientists
I6. Public support for dingo conservation
I2. Extent of uptake of policy, incentives, or new knowledge
S4. Legislation, policy, and/or funding priorities
RU6. Livestock type
O1. Development of a stewardship ethic
S4. Evidence-based education
RU4. Economic losses from dingo predation of stock
S4. Incentives or stewardship schemes
O1. Adoption of dingo-friendly management practices
RU4. Perceived financial benefit or cost of management
GS4. Land tenure
O2. Stable dingo populations
A2. Pastoralist socio-economic status
RU5. Large herbivore (exotic and native) abundance
RU5. Exotic mesopredator abundance
RU4. Profits related to stock condition
RU5. Rabbit abundance
RU5. Diversity and abundance of small vertebrates
RU2. Pasture condition
RU3. Re-distribution of seed (e.g., scatter hoarding)
RU5. Diversity and abundance of invertebrates
RU5. Seed abundance and diversity
RU5. Abundance of native predators
RU5. Vegetation cover, diversity, & biomass
ECO1. Climate
Legend
Ecosystem services or attributes
Legislated rules and knowledge
Socio-cultural factors
Economic factors
Desired practice change

Figure 2. Conceptual descriptive causal-loop diagram demonstrating variables in a proposed dingo-pastoralist social-ecological system (SES). Note that we have not made assumptions about the likely strength of the effect of one component on another. Two potential pathways are indicated by thicker lines as an example of how researchers or practitioners may select drivers for hypothesis generation and testing. Letter-number category codes depicted in Table 1. S2 = demographic trends; S4 = government resource policies; S6 = media organisations; S7 = technology; GS4 = property rights system; RU2 = growth or replacement rate; RU3 = interaction among resource units; RU4 = economic value; RU5 = number of units; RU6 = distinctive characteristics; A2 = socio-economic attributes of actors; A3 = history or past experiences of actors; A6 = norms (trust-reciprocity) and social capital; A7 = knowledge of SES / mental models; I2 = information sharing among actors; I6 = lobbying activities; ECO1 = climate patterns; O1 = social performance measures (e.g., efficiency, equity, accountability, sustainability).

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incentives are not always enough to bridge value-action-gaps (i.e. when the values or attitudes of an individual or group do not correlate with their actions) (Blake 1999), particularly if landholders already hold a strong negative view of dingoes. In a study examining willingness of Central Australian pastoralists to participate in small mammal conservation, pastoralists were generally unwilling to cease wild dog control for small financial incentives (Addison and Pavey 2017). Similarly, in a study examining conflict between community and the expanding wolf population in central Italy, most rural respondents questioned the appropriateness of financial compensation for stock losses (Vitali 2014).

We posited that historical/experiential factors influence pastoralists' dingo management practices, including the nature of folklore, stories, or "rumours" passed down by previous managers, management activities engrained in tradition (i.e., how dingoes were managed on the property in the past), length of time lived on the property, and personal experiences with dingoes (Figure 2). For example, Kellert *et al.* (1996) examined attitudes toward wolves, grizzly bears, and mountain lions in the Rocky Mountains (USA and Canada), concluding that perceptions are influenced by past and present interactions with species. Cerìaco (2012) noted that folklore strongly influenced the effectiveness of conservation programs, finding that negative folklore predicted persecution and anti-conservation attitudes toward amphibians and reptiles in Portugal. Negative stories or folklore about dingoes, passed on to successive generations of managers, may hinder efforts to change management practices. Length of time lived on a property may foster the continuation of traditional management practices, including lethal control, and the reluctance to consider new practices, particularly when proposed by external organisations. For example, central Australian pastoralists generally believed they were better placed to make decisions about land management than external agencies because their knowledge was accumulated from living on the property for a long time (Addison and Pavey 2017). Length of time on a property may also influence personal experiences with dingoes. Pastoralists in central Australia indicated a strong dislike of dingoes because of experiences with attacks on livestock. They were unwilling to accept incentives in return for cessation of lethal control (Addison and Pavey 2017, p. 338).

Pastoralists living and working in rangelands have a direct role in on-ground management (Lankester 2013; Morton *et al.* 1995; Waudby *et al.* 2012). In Australia, the pastoral industry's history of controlling dingoes is no doubt linked to perceptions of economic loss from canid predation of livestock (e.g., Prowse *et al.* 2015). However, management practices will also be influenced by interacting socio-cultural, economic, and environmental factors. Arguably, a critical challenge to canid management is the resolution of conflict between dingoes and pastoralists. Achieving resolution requires an approach that conforms to the principles of adaptive management (Argent 2009), which accommodates fluctuating drivers, and demonstrates interconnections among human constructs and canid conflict.

Benefits of a SES approach

Doherty and Ritchie (2016, p. 19) noted that an adaptive management approach to predator management should include: "…(1) definition of management goals, (2) development of management approaches to achieve these goals, (3) experimental implementation of two or more management approaches (including doing nothing as an option), (4) monitoring and analysis to evaluate the relative merits and limitations of different approaches, and (5) iterative modification of management strategies to improve management outcomes". Braysher *et al.* (2012) indicated that our imperfect knowledge of how complex and dynamic systems function and means that a risk management approach is required. Treating management interventions as experiments, monitoring and evaluating outcomes from interventions help managers form an improved understanding of the system. These approaches are encapsulated perfectly by the SES framework, which allows inclusion of dynamic drivers over time, and systematic categorisation of social-ecological interconnections, supporting scientists/policy makers in describing, predicting, and testing (monitoring) interventions.

The SES approach as applied to the dingo presents opportunities for practical research that influences policy and management around human-canid conflict. The framework we have employed defines a common terminology that was intended to facilitate comparisons of different SES and assist with increasing our understanding and ability to address problems across and within SES. Such an approach could be most useful to tailoring dingo management programs, enabling considerations of various possible management 'solutions' to conflicts. For example, after consideration of the SES (Figure 2), we may choose to examine one pathway (see bold lines in the SES), which assumes that scientific evidence influences legislation or policies. A flow-on effect is the development of educational products to disseminate new knowledge. The extent of uptake of new knowledge is influenced by socio-cultural factors, including socio-economic status, which may affect perceived financial benefits of one management practice over another, affecting the uptake of, and access to educational services and products. Perhaps little can be done to influence socio-economic status but facilitating opportunities for social learning (Schusler *et al.* 2003) might be effective. Using the framework both to compare and to contrast landholder-dingo SES in different landscapes could help identify the different types of interventions required for these systems. Pastoralists in Australia's arid rangelands (or "outback") are likely subject to vastly different overarching drivers (Stafford Smith 2008) than landholders in the higher rainfall regions of south-eastern Australia.

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We could focus on any one of the four different categories of variables identified in Figure 2 as entry points when considering possible drivers of change in future management of the SES. For example, the bottom half of the diagram concerns ecological attributes and services, so the impact of changes to key components can be traced through the system to help understand how such changes might impact on the rest of the system. Thus, if we postulate that climate change is occurring then we can trace a chain reaction through the SES from the very bottom of the diagram from 'ECO1 climate' to 'O1 adoption of dingo-friendly management practices'. We could argue that an increasingly hot and dry climate (see Bardsley and Wiseman 2016; Hughes 2011) will have a direct negative effect on the amount of vegetation cover, diversity and biomass as suggested by Morton *et al.* (2011). In turn, by following the linkages identified in Figure 2, we can see that these changes will affect condition of pastures, grazing conditions for livestock and the abundance of exotic meso-predators, small vertebrates, large herbivores and dingoes. To understand how graziers may react to these events we need to consider the interactions of these ecological changes with the identified economic and socio-cultural factors in the SES. Climate change may force more graziers out of business, reducing human impacts on dingoes. However, if that leads to growing dingo numbers (assuming they are not necessarily reduced by impacts of climate change) that may 'force' the remaining graziers to take even more stringent measures to protect their livestock from predation by dingoes. In turn, though, this action may be regulated by more stringent controls exerted by legislation, market forces (Forsyth *et al.* 2014), and/or more fluid socio-cultural factors, where societal concerns about lethal control measures (e.g., van Eeden *et al.* 2017a) and negative perceptions of the livestock industry might bring increased pressure against further use of lethal methods.

If we started our focus in another part of the diagram, for example with the socio-cultural factors, we could examine the potential impacts of one potential strategy for addressing the problem of dingoes and wild dogs, namely the formation of community-based wild dog management groups, often established to address growing impacts of wild dogs. "Based on the principle of 'nil-tenure' that takes a holistic view of the landscape, unimpeded by land ownership conventions, landholders are encouraged to view wild dog populations as a common threat that are not constrained by property boundaries and are best approached as a shared problem" (Howard *et al.* 2018, p. 245). The groups are informal or formal alliances of all affected landholders, pest controllers, community members, and political interests across private and public land tenures. Howard *et al.*'s (2018) survey of three such groups revealed a strong shared cultural identity by members who co-operated to take practical action such as increased baiting and generally reducing predation on sheep. The groups acted as a political lobby, shared knowledge, and attempted to gain wide community support for methods to control dogs. Some groups were reluctant to try new management methods, but those with wider networks were more willing to consider new ideas. The importance of collective action is clear from this research, the attitudes and cohesiveness of communities affected by wild dogs being critical in shaping collective action for wild dog management.

Conclusion

Using a systems approach to consider human–livestock–carnivore interactions can offer insights about how to create desirable transitions in rangeland SES (Boronyak *et al.* 2020). In the formulation of Figure 2, one of the principal intentions was the desire to present a set of interacting factors that could stimulate further debate and reflection on a wide range of interactions within the SES, which could draw attention to key drivers within the system and, ultimately highlight possible entry points for developing new policies and management strategies with respect to dingoes. The conceptualisation portrayed in Figure 2 can give rise to new and different thinking on what has been an ongoing issue in rangeland management for centuries. The diagram can also be used as a means of identifying new and potentially fruitful lines of research enquiry. For example, we have explicitly constructed the diagram to emphasise the interactions between ecosystems services/attributes, legislated rules and knowledge, socio-cultural factors, economic factors, and desired practice change (in this instance, focusing on adoption of dingo-friendly management practices, though there are clearly other possibilities that could be considered, e.g., maintenance of good pasture).

Previous research has tended to focus on how graziers perceive the success or failure of different interventions rather than on the ecology that helps shape the relationship between carnivores and livestock (Miller *et al.* 2015; Treves *et al.* 2016). By using an SES or alternative framework that includes these ecological mechanisms it is possible to develop better understanding of why mitigation tools succeed or fail and both to identify research and guide improved management of the carnivore-livestock conflict. For example, it highlights leverage or intervention points that can assist in the identification of key elements in a SES where relatively limited changes in practice could produce significant shifts in how the SES functions. Landholders are likely to come under increased pressure from wider society to co-exist with dingoes and to desist from harsh interventionist strategies. If this behaviour produces a cessation in the use of poison baits, it will then directly affect other biota that can be traced through the SES. Such changes may or may not have adverse impacts on the economics of pastoralism depending on whether there is a direct correlation between increasing dingo numbers and increased predation on livestock.

Alternatives to lethal control take the form of deterrents, enclosures, and improved husbandry, collectively referred to as predator smart/friendly farming. Deterrents may be visual, audio or chemical (Smith *et al.* 2020). The dingo

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fence is an example of an enclosure but can comprise any physical barrier between the carnivore and the domestic animal. Guard animals and guard humans are examples of 'improved' husbandry, as are variations in grazing intensity. The adoption of these alternatives is relatively limited, though van Eeden *et al*. (2018a,b) have identified livestock guardian dogs and flashing night-lights as the most effective forms of preventive innovations.

Encouragement of further innovative management and use of alternatives will require the creation of a supportive environment, which primarily means political and industry support involving open dialogue between stakeholders. Innovation will involve addressing legislation, funding and government programmes that currently focus on lethal control. Partnerships between interested parties that can open new dialogues may hold the key to changing management practices, as illustrated by new rangeland partnerships in Montana (Young *et al*. 2019). Boronyak *et al*. (2020, in press) concluded that an 'enabling environment' must be created that "provides social support, funding, and builds capacity (skills, knowledge and confidence) to use preventive tools and practices."

The SES framework may also be useful in considering new approaches to rangeland management beyond a narrow focus on the issue of dingoes. For example, recent proposals by Briske *et al*. (2020, in press) suggest that "the challenge may be how to best transform rangeland social–ecological systems to provide optimal combinations of ecosystem services to meet the needs of all citizens, while improving the well-being of millions of rangeland residents who are highly dependent upon provisioning services." The implication is that future rangeland management must seek to balance trade-offs between the needs of existing landholders, who rely on income from domesticated livestock and the contribution to that from ecosystem capacity, and maintenance of diverse ecosystem services to benefit wider society. Indeed, it is the changing demands of that wider society that can already be recognised as having an impact on land use and economy in the Australian rangelands. For example, Holmes (2002) referred to a 'post-productivist transition' in which new interests and land uses are appearing in the landscape as traditional grazing activities face a decline in income; one recent study describes Australian rangeland pastoralism as becoming a marginal economic activity (Holmes 2015, p. 609). Holmes (2002) mentioned renewed Indigenous occupancy, the growth of conservation and tourism, with significant changes in land ownership, property rights, investment sources and power relations, all of which are creating new conditions under which pastoralism is operating. While these changes are uneven and vary considerably in their intensity, they represent another factor in evolving relationships within the SES.

Using a SES framework to diagnose the issues influencing canid management could help re-focus the debate about the impact of dingoes and their role as apex predators and ecological importance on developing practical and effective on-ground outcomes. The SES approach provides an opportunity to recalibrate knowledge of human-carnivore interactions, to develop holistic and inclusive approaches to predator research, to engage more meaningfully with land managers, and facilitate behavioural change with lasting conservation outcomes in those areas where non-lethal management options are needed.

Conflicts of Interest

The authors declare there are no conflicts of interest.

Acknowledgements

We thank P. Bowen of Murray Local Land Services for her thoughts on developing and applying social-ecological systems frameworks to natural resource management problems. We also thank K. Thompson for her comments on an early draft of the paper. This research did not receive any specific funding.

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APPENDIX I

Review of social-ecological systems approaches to resolving human-carnivore conflicts.

Focal carnivore species	Conflict	Social-ecological system	Key biophysical and social factors of the model	Key methods/tools	Conceptual approach	Citation
African wild dog (*Lycaon pictus*) Cheetah (*Acinonyx jubatus*) Leopard (*Panthera pardus pardus*) Lion (*Panthera leo*)	Evaluation of the ecological, socio-economic, and political factors influencing large carnivore conservation	Africa	Fourteen factors identified and arranged under three categories: political, socio-economic, and ecological.	Review of existing literature on large African carnivore conservation	Not strictly identified as a social ecological system approach. Key factors influencing carnivore conservation arranged under three tiers and according to their level of impact on long-term conservation.	Winterbach *et al.* 2012
Bengal tiger (*Panthera tigris tigris*)	Understanding the extent of human impacts on wildlife and their habitats.	Chitwan - Terai foothills of the Himalayas above the Indo-Gangetic Plain, Nepal	Broadly defined as the human subsystem (community and local residents) and the natural subsystem (land cover and wildlife), the interactions between these main components, and acknowledging the role of telecoupling processes.	Analysis of the patterns, causes, and consequences of changes in wildlife population and habitat, human population and land use using published research on the focal area to understand relationships between humans and tigers.	Coupled human and natural systems approach (CHAN) that defines interrelated system components, including telecouplings (socioeconomic and environmental variables that interact over distances).	Carter *et al.* 2014
Brown bear (*Ursus arctos*) Lynx (*Lynx lynx*) Wolf (*Canis lupus*) Wolverine (*Gulo gulo*)	Improving community tolerance of reintroduced carnivores	Sweden	Focuses on three generic facets: system context or dimensions (biophysical; socio-cultural; political-institutional), responses of actors, and outcomes.	Based on a workshop of Swedish social scientists involved in large carnivore research.	Integrated analytical model of human responses to large carnivore governance with five additional concepts to apply to large carnivore governance	Sjölander-Lindqvist *et al.* 2015

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APPENDIX 1

Focal carnivore species	Conflict	Social-ecological system	Key biophysical and social factors of the model	Key methods/tools	Conceptual approach	Citation
Brown bear (*Ursus arctos*)	Understanding factors that influence human-bear coexistence	Foothills of the Carpathian Mountains, Transylvania, Romania	Three coexistence strands identified (landscape-bear; landscape-human; management).	Strands identified via qualitative content and discourse analysis of 71 semi-structured interviews.	Not strictly identified as a social ecological system approach. Each strand identified key ecological and social factors that interact to influence threats and opportunities around coexistence.	Dorresteijn *et al.* 2016
Tigers (*Panthera tigris*) Wolverines (*Gulo gulo*)	Illegal poaching of both species	Tigers – Nam Et-Phou Louey National Protected Area, Laos Wolverines – northern Sweden	Defined as a series of human motivations/ behaviours around poaching and carnivores' vulnerability/ behaviours in relation to poaching	Review of literature around motivations for poaching and animal vulnerability to poaching, and of policy interventions and associated feedbacks for the focus species	Nested multi-level framework focused on factors accepted as influencing human motivation for poaching and animal vulnerability to poaching	Carter *et al.* 2017
Güiña (*Leopardus guigna*)	Drivers of güiña decline in southern Chile	Araucania region of southern Chile	Data on human-predator relationship, predator presence/absence, and landscape configuration and habitat quality	Remote sensing, wildlife survey, and social research	Integrated socio-ecological framework comprising four sequential stages	Gálvez *et al.* 2018
Black bears (*Ursus americanus*)	Garbage-related conflicts between humans and bears	Durango, Colorado	Range of factors identified with specific examples from within the SES of interest	Identification of previously unidentified feedbacks and relationships affecting the success of the program, and recommendations to address these feedbacks and reduce conflict	Conceptual three-tiered model of human-wildlife interactions with feedback loops. Tiers defined as: 1) overarching factors affecting human-wildlife interactions; 2) external influences on individual's behaviour; 3) individual attributes affecting behaviour	Lischka *et al.* 2018

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